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COSMIC MICROWAVE BACKGROUND SPECTRUM MEASUREMENTS

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ABSTRACT: This paper reviews the three major cosmic microwave background radiation (CMBR) spectrum measurement programs conducted and published since the last (XVII) IAU General Assembly. The results are consistent with a Planckian spectrum with temperature 2.72 ± 0.03 K spanning a wavelength range of 0.1 to 12 cm. Limits on possible distortions and implications are outlined. Ongoing and future measurements are discussed.

1. INTRODUCTION

As of the last IAU General Assembly (1982) the CMBR spectrum had been confirmed as being thermal. With the CMBR reputedly established as the relic radiation from the Big Bang, what is the point in measuring the spectrum more accurately? There are two important reasons: (1) In 1982 the Woody and Richards (1981) measurements were the most accurate and they showed an unexpected small deviation near the peak. (2) There are potentially a number of cosmologically revealing spectral distortions, some of which are very likely, while others are highly speculative. Figure 1 shows some examples.

A Compton distortion is the most likely spectral deviation from a Planckian (blackbody thermal) spectrum. If after a redshift of about 4×10^4 an energy source heats the ionized intergalactic matter, the hot electrons scatter low energy photons to higher energy, making the CMBR cooler at frequencies below the peak and hotter above the peak at short wavelengths ($\lambda < 0.1$ cm). This process occurs in X-ray emitting galactic clusters and is called the Sunyaev-Zeldovich effect. Because the Sunyaev-Zeldovich effect is small and localized to known small angular areas on the sky (X-ray clusters), it is easier to detect by anisotropy or beam switching measurements. However, the intergalactic medium is currently nearly fully ionized and is very much hotter than the CMBR so it should produce very much the same effect. A detection of this distortion measures the Comptonization parameter y,

$$y = \int \frac{kT_e}{m_e c^2} n_e c \sigma_T dt$$

which is the number of Compton scatterings times the dimensionless electron temperature.

If the matter of the universe is heated with extra energy before recombination, there will still be cooling below the peak and heating at high frequencies but bremsstrahlung will add extra low-frequency (or long-wavelength) photons. Thus the temperature will be higher at low and high frequencies but cooler in the middle frequency range. For energy release between redshifts of about 4×10^4 and 10^6 the number of Compton scatterings is sufficient to bring the photons into thermal equilibrium with the primordial plasma but the bremsstrahlung and other radiative processes

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do not have sufficient time to add enough photons to recreate a Planckian distribution. The resulting distribution is a Bose-Einstein spectrum with a chemical potential, μ, that is exponentially attenuated at low frequencies $\mu = \mu_o e^{-2\nu_o/\nu}$. The Planckian spectrum is the special case of the Bose-Einstein with zero chemical potential.

The injection of energy into the universe discussed above results in cooling for the frequencies below the peak with the maximum decrease in the range from about 3 to 10 cm wavelength (10 to 3 GHz). This corresponds to a photon under population (positive chemical potential) in that frequency region. If a process were to add photons in this range, one would observe a bump (negative chemical potential). There are a number of potential processes that could add photons to the CMBR. After the distortion reported by Woody and Richards a number of theorists added a bump to the peak by creating dust very early and aligning the 10 micron silicate feature with the CMBR peak to produce an apparent excess. It is conceivable that longer wavelength lines could add to the CMBR. Another possible mechanism is the cosmological production of weakly interacting particles that decayed into a photon and other daughters, such as an unstable massive neutrino. The decay product photons would add a bump to the spectrum. Even though the photon probably would have a sharply defined frequency, it would be smeared in frequency by the thermal energy of the parent, the varying redshifts at the times of the decays, and successive Compton scatterings with the plasma.

Even more speculative theories predict various other types of distortions. For example Georgi, Ginsparg and Glashow (1983) developed a two-photon elementary particle theory which contained the standard photon that astronomers know and love and a photon that interacted extremely weakly with matter but which could undergo identity oscillations with the standard photon. This would result in an apparent oscillation of the CMBR temperature with wavelength.

Three recent measurements of the CMBR spectrum: (1) Meyer and Jura (1985), (2) Peterson, Richards, and Timusk (1985), and (3) Smoot *et al.* (1985*a*) have greatly reduced the uncertainty in the spectrum of the CMBR for wavelengths between 0.1 and 12 cm.

2. OBSERVATIONS OF INTERSTELLAR CN TEMPERATURE: MEYER AND JURA

The concept of the measurement is quite simple: find a cold molecular cloud containing optically thin CN that is back lit by a strong source with a good continuum near 3874 Å. Look for the CN R(0), R(1), R(2), and P(0) absorption lines. By carefully determining the relative line strengths and making a small correction for saturation one can determine the excitation temperature of the CN molecules and obtain an upper limit on the CMBR temperature at the appropriate wavelength. If the conditions are sufficiently well understood, the CN temperature can be corrected for local excitations and a best estimate derived for the CMBR temperature.

David Meyer and Michael Jura (1984, 1985) used the 1872 element Reticon photodiode detector on the Lick 3.0 m telescope to obtain high signal-to-noise observations of the 3874 Å band of interstellar CN toward ζ Oph, ζ Per and o Per. A careful set of procedures and the improved instrumentation resulted in observations that improved significantly on previous results. In the course of their measurements they discovered a weak telluric feature at 3873.1 Å which may have confused earlier measurements. (The earlier measurements did not have the resolution or the fortune to have the earth's velocity around the sun separate the telluric and ζ Oph CN line. The saturation-corrected CN line strengths yielded CN excitation temperatures of 2.72 $\pm$ 0.05 K, 2.76 $\pm$ 0.05 K, and 2.78 $\pm$ 0.07 K respectively for the J = 0 − 1 rotation transition at 2.64 mm. The excellent agreement between the three temperature confirms the expectation that the CMBR is primarily responsible for populating the excited rotational levels of the interstellar CN. In each case these are upper limits for the temperature of the CMBR. The consistency of the results argues strongly against any significant local contribution to the excitation of the CN, since the physical conditions along the line of sight to these three stars are noticeably different.

After a small correction for local CN excitation due to electron impact, they found a CMBR brightness temperature of 2.70 ± 0.04 K at a wavelength of 2.64 mm. This value is currently the most precise determination of the CMBR temperature at any wavelength.

The measured CN $J = 1 - 2$ excitation temperature is 2.76 ± 0.20 K at a wavelength of 1.32 mm. The fact that the three separate CN temperature measurements give a CMBR temperature consistent with a 2.7 K blackbody spectrum reinforces the explanation of the CMBR as the universal thermal background relic of the primeval fireball. A more accurate measurement of the 1.32 mm wavelength temperature would be most valuable.

This excellent work tightly constrains the fits to potential spectrum distortions by forcing them to go through the 2.64 mm data point. It is also the only experiment that is likely to be a significant check on the COBE satellite spectrum measurement. For these reasons I think it important that it be reviewed carefully and checked appropriately.

3. HIGH FREQUENCY MEASUREMENTS: PETERSON, RICHARDS AND TIMUSK

The Berkeley group of Professor Richards has continued their program of high-frequency CMBR spectrum measurements that began with the PhD thesis of John Mather, followed by the measurements of Woody and Richards (1981). Jeff Peterson, Paul Richards, and Tom Timusk (1985) have made new direct infrared measurements of the CMBR spectrum. They used much of the same equipment or designs of the earlier work, with the important modifications of using a wheel of five band-pass filters instead of a Fourier transform spectrometer and using an inflight calibrator.

They used a ^{3}He bolometer as the basic detector. The bolometer changes temperature in response to the power incident upon it and its impedance is a very sensitive function of its temperature. Any one of five specially designed filters can be selected to determine the passband on the range from 2.3 to 11.0 cm^{-1} using a filter wheel just in front of the bolometer.

A large assembly consisting of ground shield, flared antenna, Winston concentrators, and lenses collects radiation from the sky and focuses it on the detector. The antenna system has a beamwidth of 10 degrees. At the output of the flared antenna/large Winston concentrator is a switch which can change the input from the compound horn viewing the sky to an internal blackbody reference viewed through similar collecting optics. In this way the power received from the CMBR is compared with that from the liquid-helium-cooled 3.2 K calibrator.

The entire assembly including the large compound-horn antenna is liquid-helium-cooled. Boiled-off helium is used to keep the optics cooled, flushed, and to prevent air from freezing on the antenna. The photometer is balloon-borne to get above most of the atmospheric emission so that the CMBR is the dominant source of radiation. Residual atmospheric signal and ground radiation are determined through zenith angle scans. The atmospheric signal and antenna emission are subtracted from the measured total flux to determine the CMBR absolute flux.

Measurements were made in November 1983 and new measurements are planned for spring 1986. All five bandpass temperatures are consistent with a mean temperature of 2.78 ± 0.11 K. No significant deviation from a thermal spectrum has been detected. The combination of the results from Meyer and Jura and these new results supplant the older Woody and Richards data. We can conclude that while those earlier data convincingly show the expected Wein downturn firmly establishing the thermal nature of the CMBR spectrum, the claim of distortions is most likely incorrect. (As an aside I note that the new data of Peterson, Richards and Timusk do have a similar shape to the older data of Woody and Richards, but the magnitude is smaller and the impugned distortion not statistically significant. I have to wonder if it might not be an instrumental artifact having to do with the collection optics.) I have dropped the Woody and Richards data from plots of spectrum measurement data and from analyses of potential distortions.

4. LOW FREQUENCY MEASUREMENTS: SMOOT *et al.*

By the late 1970's the need for improved low-frequency measurements of the CMBR spectrum was evident. An international collaboration was formed to make these measurements (Smoot *et al.* 1983). The concept of the experiment is again simple. A radiometer, a device whose output is proportional to input power over a defined bandwidth, measures the difference in power received from a known-temperature absolute-reference load and from the sky. Knowing the calibration coefficient of the radiometer, one can determine the absolute amount of power received from the sky. By accounting for all the extra sources of radiation the residual is the CMBR flux. If the absolute reference load temperature is very close to that of the CMBR and the same radiometer measures the strengths of the extra sources of radiation, the effects of calibration error are eliminated to first order. We use a liquid-helium-cooled load with an effective thermodynamic temperature of 3.8 K which is to be compared to the 2.7 K temperature of the CMBR. This absolute reference cold load is a critical component of the experiment so we spent a large portion of our effort making it a good cold load whose emitted power would be well known.

The largest extra signal observed was atmospheric emission. We determined the atmospheric emission by observing the total power from the sky at varying zenith angles, thereby modulating the amount of atmosphere observed. By correlating the observed signal with airmass for zenith angle scans we obtained the vertical (zenith) atmospheric signal. We designed and conducted the experiment so that all other sources of emission were small and easy to correct or were negligible.

The radiometers were superheterodyne radio receivers whose input was switched rapidly between two receiving antennas. One antenna, the secondary, viewed a cold stable load whose power output was very near that of the zenith sky and the absolute-reference cold load. Typically we used the zenith sky as the secondary load, although we occasionally used the north celestial pole or a cryogenically cooled load. The radiometer was mounted so that the other antenna, the primary, could be made to view in rapid succession the absolute-reference cold load, the zenith, and various zenith angles as well as a warm calibration load. Since the primary signal was compared to the secondary at a rate of 100 times a second, the effect of gain and noise power fluctuations of the receiver was reduced and averaged out since all signal levels measured were kept small. The relatively rapid cycling of the targets kept the observing cycle time relatively short, minimizing the effects of long term drifts and atmospheric emission variation due to changing weather conditions.

The collaboration program was to build five such radiometers, each scaled by its wavelength, that would use the same absolute-reference cold load, make observations at the same location interleaved in time in order to have conditions as similar as possible, and to analyze the data together in an effort to get the best absolute measurements possible and to improve the sensitivity for detecting spectral distortions. The lowest frequency radiometer, operating at a wavelength of 12 cm, was built and operated by a group from Milano (Giorgio Sironi *et al.* 1984). CNR Bologna (N. Mandolesi *et al.* 1984) provided and operated a 6.3 cm wavelength radiometer. Haverford College (Partridge *et al.* 1984) constructed and ran a 3.2 cm wavelength radiometer which operated as a semi-automated atmospheric emission monitor to provide continuous track of the atmospheric signal. The Berkeley group (Smoot, *et al.* 1983, 1985*a*) provided the absolute-reference cold load and the three highest frequency radiometers, operating at wavelengths of 3 cm (Scott Friedman, *et al.* 1984), 9 mm (De Amici, *et al.* 1984, 1985), and 3 mm (Witebsky, *et al.* 1986). The primary observations were made in July 1982 and September 1983. In August 1984 my group returned for additional measurements and to try out a new tunable wavelength radiometer.

5. INTERPRETATIONS

The data are all well fitted by a Planckian spectrum with a temperature of 2.72 ± 0.02 K. The results of the measurements discussed here are listed in Table 1 and are shown in Figure 2 along with those of previous experiments. Also shown are four sample distortions. These are not the best fit distortions but the distortions resulting from using the 95% confidence level parameters in the direction of most cosmological interest. Since one listener commented, "I did not realize that the distortions occur just outside the range of your measurements," I will emphasize here that I

References	Wavelength (cm)	ν (GHz)	T_{CBR} (K)
Sironi (Smoot *et al.* 1985*b*)	12.0	2.5	2.78 ± 0.13
Mandolesi (Smoot *et al.* 1985*b*)	6.3	4.75	2.71 ± 0.08
Friedman (Smoot *et al.* 1985*b*)	3.0	10.0	2.75 ± 0.08
De Amici (Smoot *et al.* 1985*b*)	0.909	33.0	2.81 ± 0.12
Witebsky (Smoot *et al.* 1985*b*)	0.333	90.0	2.57 ± 0.12
Meyer & Jura 1985	0.264	113.6	2.70 ± 0.04
Meyer & Jura 1985	0.132	227.3	2.76 ± 0.20
Peterson,	0.351	85.5	2.80 ± 0.16
Richards, &	0.198	151	$2.95^{+0.11}_{-0.12}$
Timusk 1985	0.148	203	2.92 ± 0.10
	0.114	264	$2.65^{+0.09}_{-0.10}$
	0.100	299	$2.55^{+0.14}_{-0.18}$

Table 1: Measurements of the Cosmic Background Radiation Temperature

have chosen these distortions to be as large as possible and still be barely consistent with the data and also be reasonably visible. One curve, number 3, does in fact have its maximum deviation at about 4 cm wavelength which is in the range of our measurements but is difficult to see compared to the rest.

One can do a whole series parameter fits using various assumptions about the density of the universe, the baryon (electrons for Compton scattering) density, and the epoch and nature of the energy release. These families of parameter limits can then be converted into limits on energy release in those situations. One can then make a series of curves showing maximum allowable fractional energy release, $\delta E/E_R$, as a function of redshift for various densities.

The fractional energy release limits can then be used to set limits on processes of cosmological interest. Examples of these are: (1) The spectrum of adiabatic density perturbations (Sunyaev and Zel'dovich 1970) (2) The spectrum of primordial turbulence and vorticity (Illarionov and Sunyaev 1974; Chan and Jones 1976) (3) Annihilation of matter and antimatter in the early universe (Stecker and Puget 1972; Sunyaev and Zel'dovich 1980) (4) Energy release by evaporating primordial black holes or unstable (decaying) particles (Dolgov and Zel'dovich 1981; Silk and Stebbins 1983) (5) an improved estimate of n_γ.

From the constraints on the chemical potential the energy in turbulence on scales which are currently 30 kpc to 4 Mpc is less than one per cent of that in the CMBR. This limit is sufficient to rule out turbulence and vorticity as the drivers of galactic formation. Similar arguments can be made regarding adiabatic perturbations and the limits are borderline. However, the small scale anisotropy measurements place an even more restrictive limit providing re-ionization of the universe did not happen sufficiently early that the CMBR is scattered and the distortions erased. Theorists now indicate that they need dark matter to generate galaxy formation with those limits.

The annihilation of matter and antimatter is constrained similarly by the limits on energy release provided by the limits on y and the chemical potential μ. If the Grand Unification and

Inflation theories were well established, then the excess of matter of antimatter and the possibility of residual unannihilated antimatter might be of no concern. For redshifts between 10^6 and 4×10^4 the amount of energy released in annihilation is less than 1% of that in the CMBR. After a redshift of about 4×10^4 the limit is about 5%.

The decay of massive particles can also produce a non-Planckian spectrum. Silk and Stebbins (1983) have shown that one can use the limits on CMBR spectral distortions to rule out weakly interacting particles with lifetimes, τ less than the Hubble time (10^{10} years) and greater than about 0.1 years and masses, m, between about 10^{-6} and 10^6 eV, except for a small strip along $m^2\tau = 10^{10}(\mathrm{eV})^2$ years which is hidden in the interstellar background.

6. FUTURE

Just as at the last IAU meeting, we can look forward to additional new measurements and results from programs that are now underway. The first of these is a continuation of efforts by some members of our international collaboration. After fitting to the now allowed distortions it was clear to us that additional low frequency measurements would be useful in constraining possible distortions. The group from Milano (Giorgio Sironi *et al.*) has planned continued observations using the 2.5 GHz (12 cm wavelength) radiometer in combination with a new 600 MHz (50 cm wavelength) radiometer. These would use a new helium-cooled termination for a cold load and would compare the old 2.5 GHz measurements with the large liquid-helium-cooled load as a check on systematic errors. Observations were planned to begin in late May 1985; however, when members of my group from Berkeley traveled there to assist in the setting up and observations, we found the generally poor and rainy weather in Europe had delayed the construction of the radiometer. We helped Milano finish the assembly and begin the early testing but found that the site we had selected had so much radio interference that we could not find a clear bandwidth 5 MHz wide. Giorgio Sironi conducted a search for a new site and found that Alpe Gera, a deep valley in the Alps, might be a suitable site. Just before the IAU meeting I got a telex that his group had made preliminary measurements and was going back to Milan to analyze them. If this site is satisfactory, we can expect a new measurement at 50 cm; however, one should realize that because of the galactic background and the other difficulties in doing this experiment at such a long wavelength, the errors on this result will be significantly larger than for many of the higher frequency measurements.

At Berkeley (Smoot *et al.*) we are planning to make tunable radiometer measurements to cover more throughly the region of our previous fixed-frequency measurements and to cross-check those measurements since they strongly restrict possible distortions and thus important cosmological processes. We have a tunable radiometer that operates reasonably over the range 2 to 8 and 8 to 18 GHz (2 to 15 cm wavelength) and are working on improving its performance so that we can make high quality measurements. We are in the process of designing a radiometer tunable over the range 1 to 2 GHz (15 to 30 cm wavelength) in an effort to get new measurements over the lowest reasonably accessible frequency range. Depending upon funding, technical success, and the weather we hope to return to our observing site at White Mountain in the summer of 1986.

The Berkeley group of Richards *et al.* is planning to refly their balloon-borne five-frequency photometer next year to obtain additional data and perform cross checks that were not obtained on the previous flight. Future effort depends upon results and competing projects.

The Princeton group of Dave Wilkinson and graduate student Dave Johnson made a balloon flight in April with a 1.2 cm wavelength (24.8 GHz) spectrometer as a test of their spectrum experiment concept. The first results should be available soon. If the concept appears good, they are considering adding more frequencies (46 and 90 GHz) and reflying the payload.

The British Columbia group (Herb Gush and Mark Halpern) are planning a flight of new design of Gush's (1984) rocket-borne Fourier-transform spectrometer. The spectrometer has two channels covering 2 to 25 cm^{-1} and 2 to 40 cm^{-1}. The expected resolution is 1% at the peak. They are in a delicate position since the Canadians have terminated their rocket program. They have one rocket they can use from the U.S. range at White Sands.

In 1988 shortly before the next IAU General Assembly in Baltimore the COBE (Cosmic Background Explorer) Satellite is expected to fly and the FIRAS (Far Infrared Absolute Spectrophotometer, Mather 1982) experiment will measure the high frequency spectrum of CMBR over the wavelength range 0.01 to 1 cm with a spectral resolution of about 5%. Figure 3 shows the expected sensitivity superimposed on a summary plot of measurements to date. The precision of the measurement will be extraordinarily good. We can expect that the limits on the Comptonization parameter y may be reduced to the 10^{-4} level. This would restrict the ionized intergalactic medium severely and might allow us to prove that the bulk of the CMBR photons has not scattered since recombination at a redshift of about 1000. If there are significant distortions produced before recombination, the COBE FIRAS experiment may be sensitive enough to detect the second order effects that result in excess recombination lines (Lubyarsky and Sunyaev 1983).

The COBE FIRAS measurements would bring additional information to bear on potential distortions characterized by a chemical potential where the distortion is manifest at lower frequencies than its measurements. How powerful this information is depends upon the actual value and character of the results. As can be seen in the earlier plots, larger distortions — i.e. larger chemical potentials — are accomodated by having elevated temperatures in the high frequency region. If the COBE FIRAS experiment can make a very accurate absolute temperature measurement as well as the good relative internal measurement, it will tie down the high frequency temperature extremely accurately. We can expect about a factor of two or more reduction of current limits on the chemical potential type distortions if the results are in agreement with the Meyer and Jura results. Hopefully new low frequency measurements will provide additional improvement in accuracy in determining or setting limits on such distortions.

At about the time of the next IAU General Assembly we can expect a lot of activity and new results on the CMBR spectrum.

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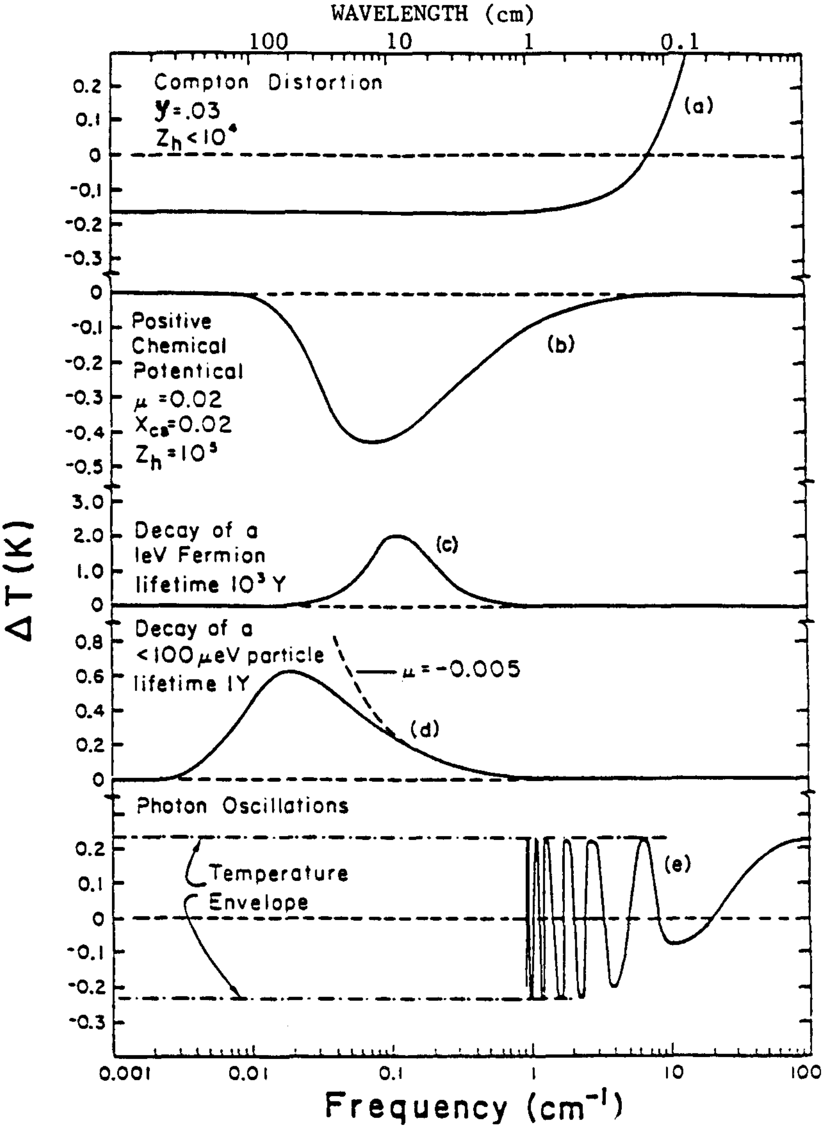

Fig.1. Potential distortions of CMBR spectrum.

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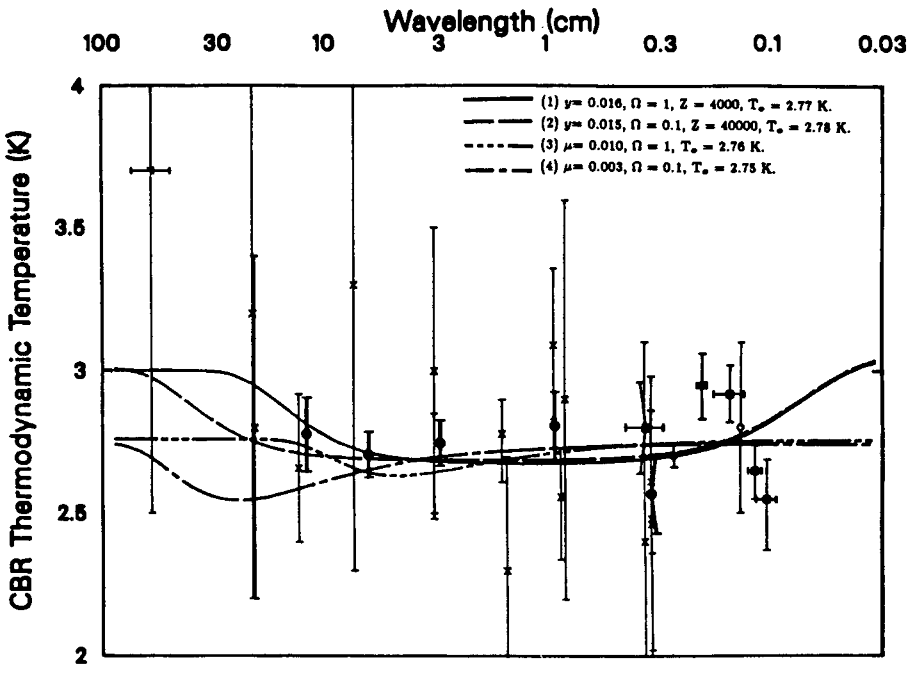

Fig.2. Summary plot of data with four 95% C.L. distortions superimposed.

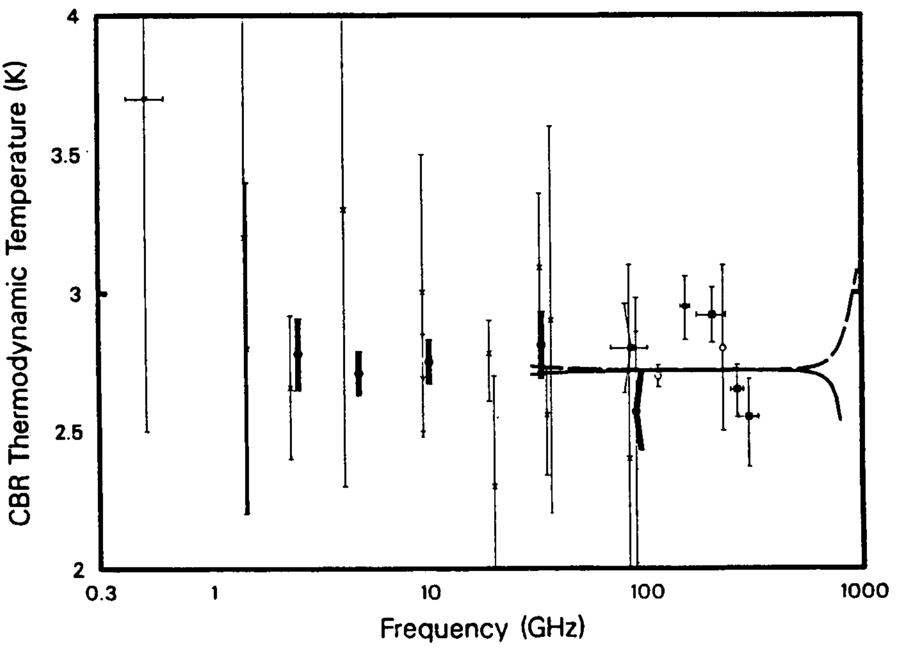

Fig.3. Summary plot of data with expected COBE FIRAS sensitivity superimposed.

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